Zernike-type phase contrast X-ray microscopy at 4 keV Photon energy with 60 nm resolution

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Outline

Introduction: The ID 21 X-ray microscopes (using Fresnel zone plates):

- scanning X-ray microscope (SXM), 2 – 8 keV, elemental mapping of medium Z elements and chemical analysis (XANES) by fluorescence
- full-field transmission X-ray microscope (TXM), 4 keV, high-resolution imaging, phase contrast

Principle of Zernike phase contrast

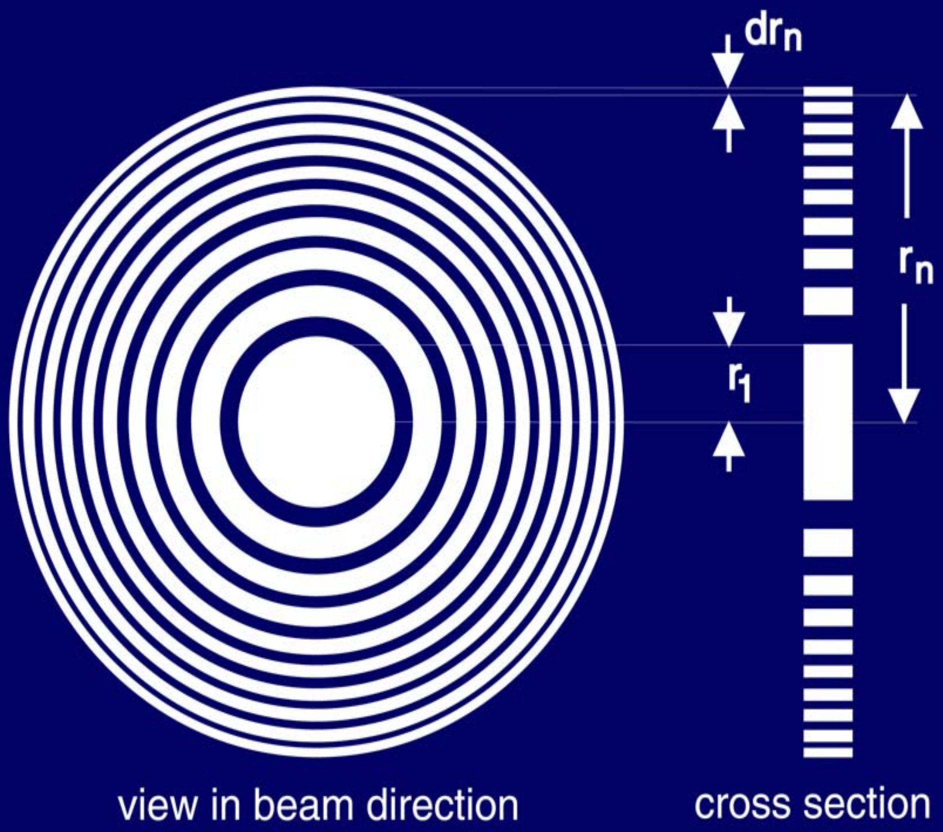
Application examples

Zernike phase contrast X-ray microscopy on microelectronics samples

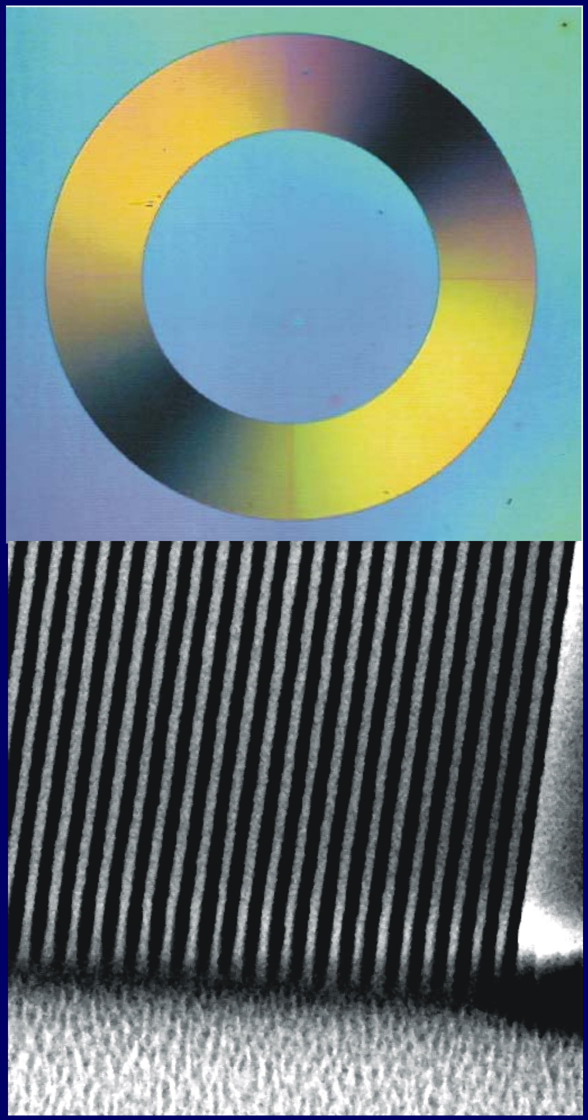
- SEMATECH serpentine resistor
- AMD microprocessor

Summary, Conclusions and Outlook

Fresnel zone plates as X-ray lenses



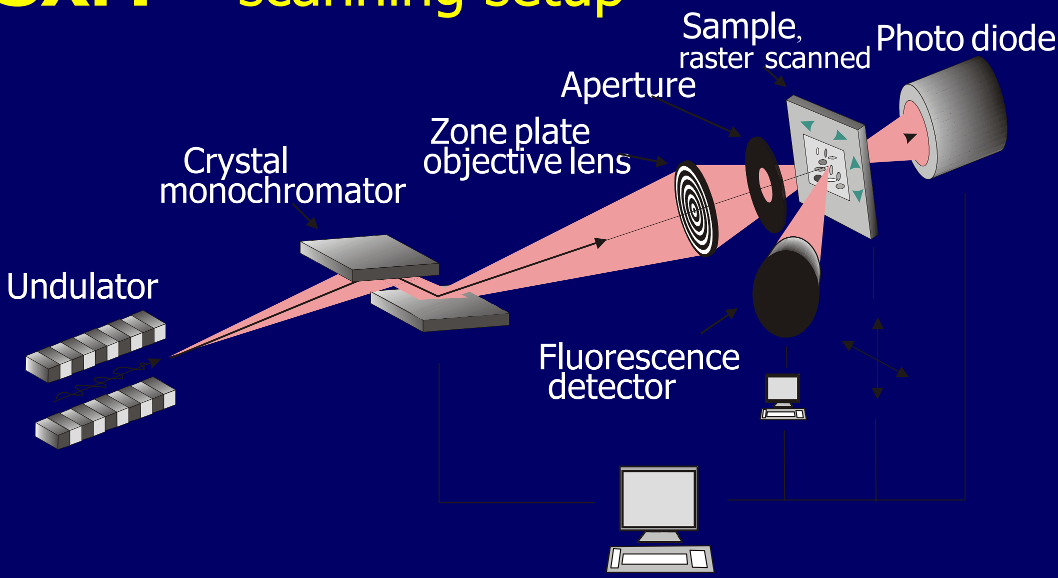
focal length $f = 2 \cdot r_n \cdot dr_n / \lambda$
resolution $\delta = 0.61 \cdot \lambda / \text{N.A.}$ $\rightarrow \delta = 1.22 \cdot dr_n$



Light microscope image (top) and Scanning electron micrograph (bottom) of a Au Fresnel zone plate, fabricated by D. Hambach (IRP, Universität Göttingen, Germany)

Zone-plate based X-ray microscopes: two optical schemes

SXM – scanning setup



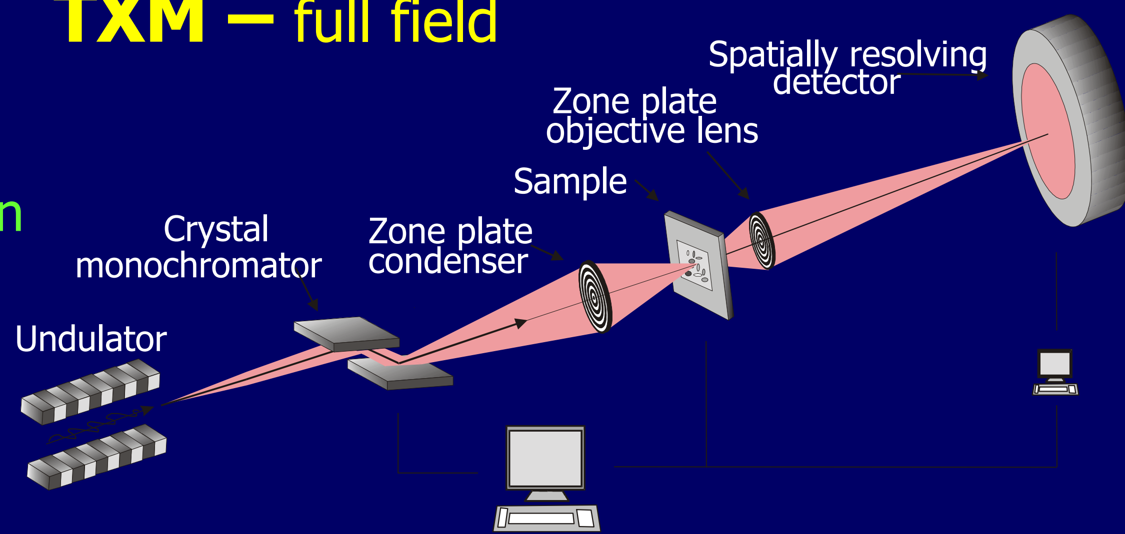
Advantages

- dose efficient
- multiple detection in parallel
- applicable to bulk materials
- easily variable image field size

Disadvantages

- relatively slow
- sophisticated instrument

TXM – full field



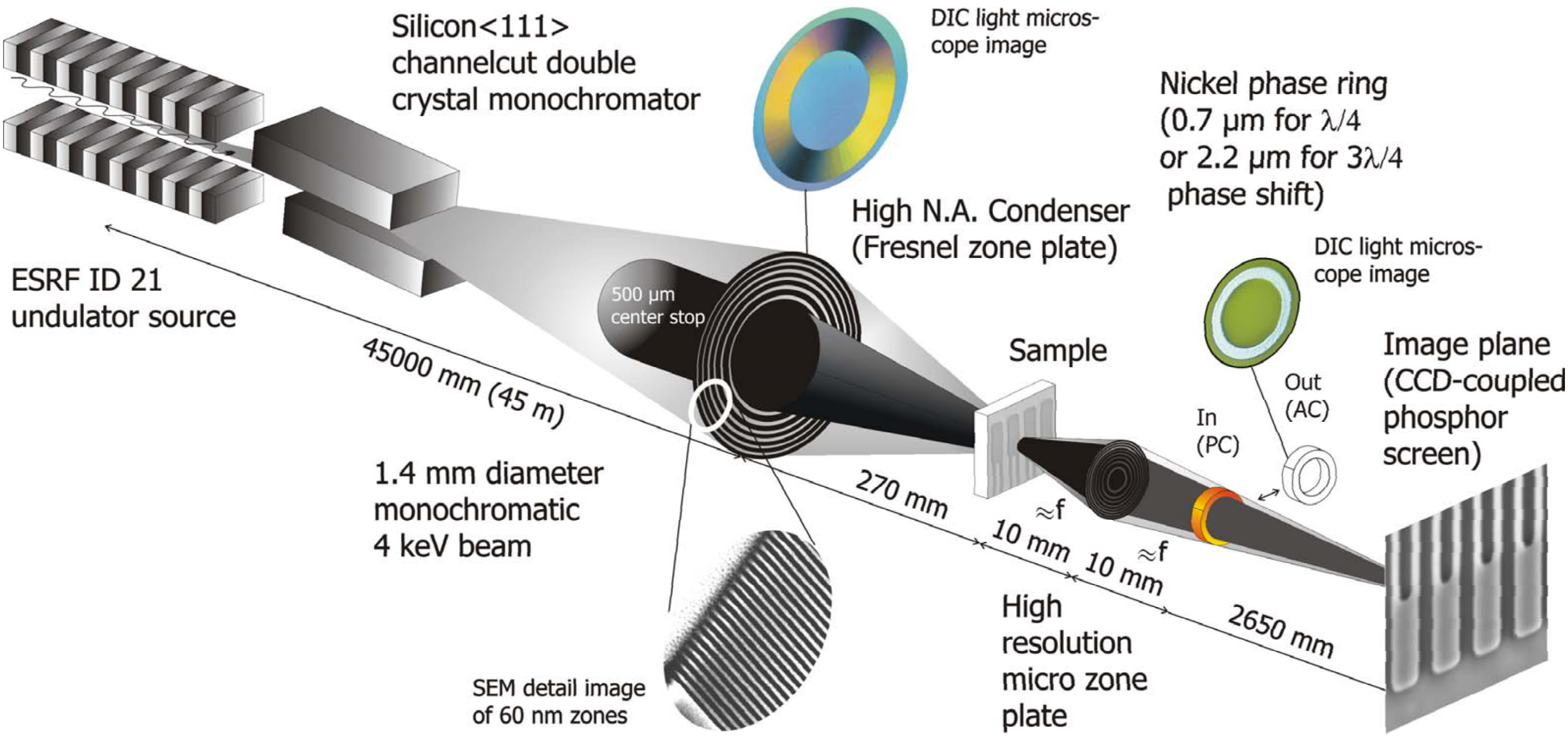
Advantages

- fast - suitable for tomography
- relatively simple instrumentation
- higher spatial resolution

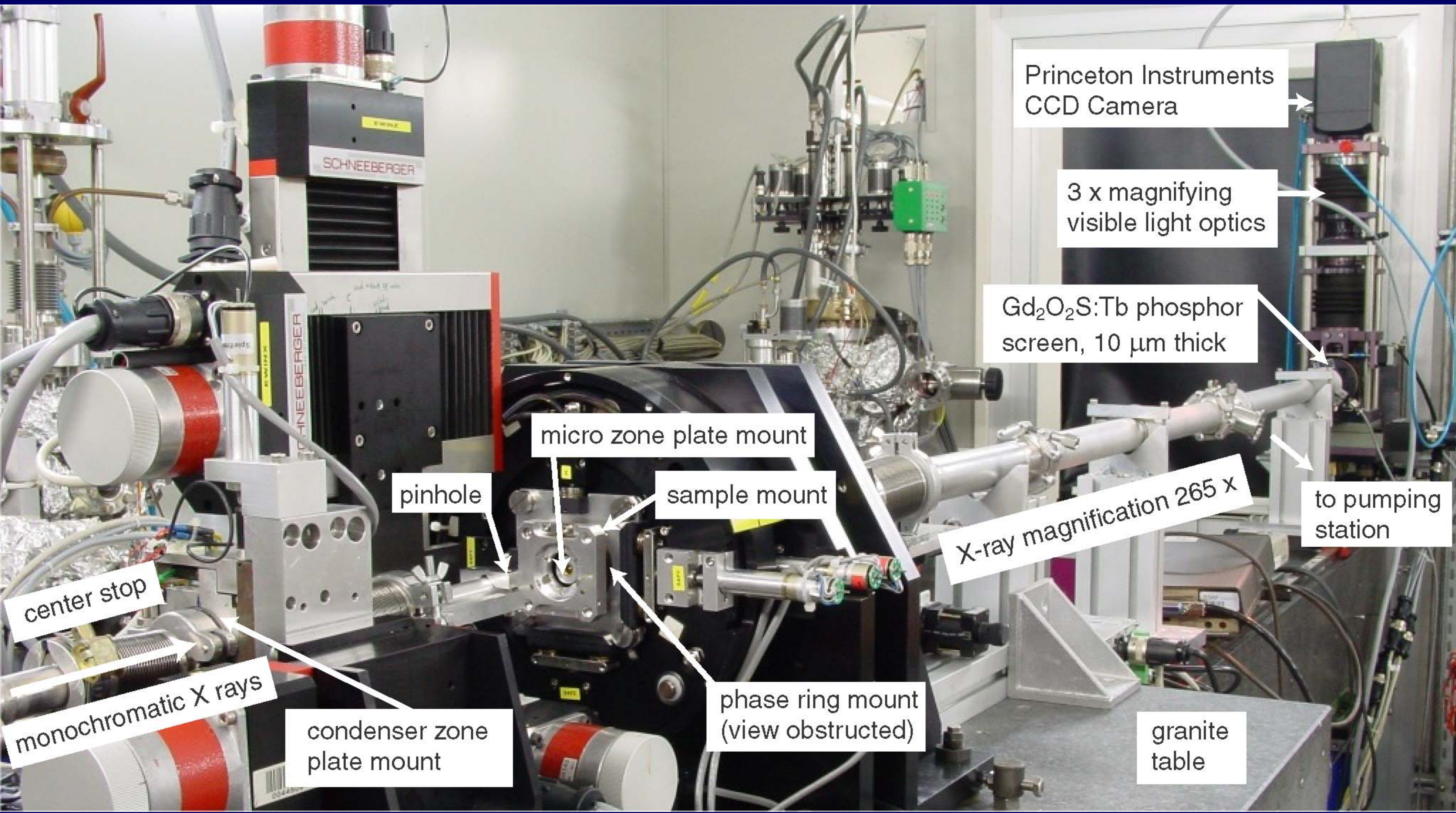
Disadvantages

- transmission detection only
- dose inefficient

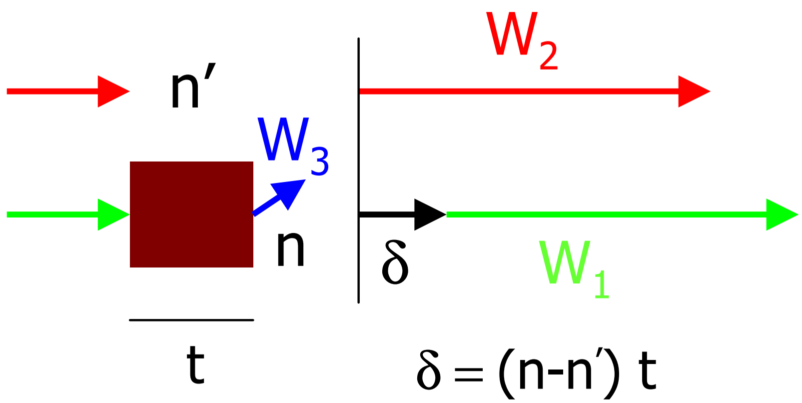
Zernike Phase contrast: Schematic of the ID 21 TXM setup

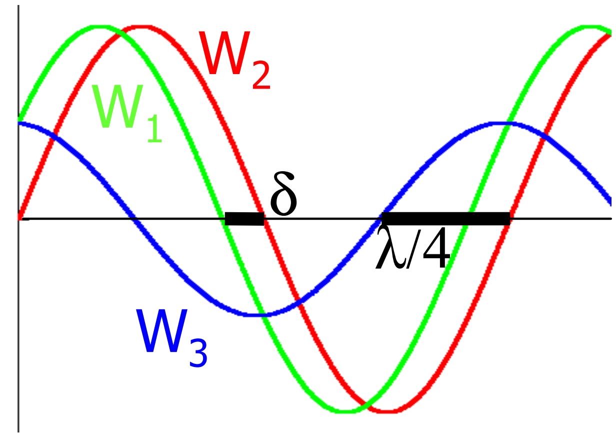


Photograph of the ID 21 full-field microscope (TXM) endstation setup for Zernike phase contrast imaging

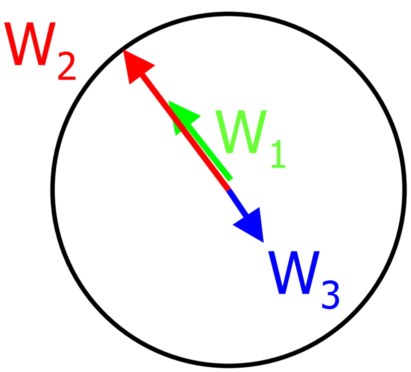


Zernike Phase contrast - Principle

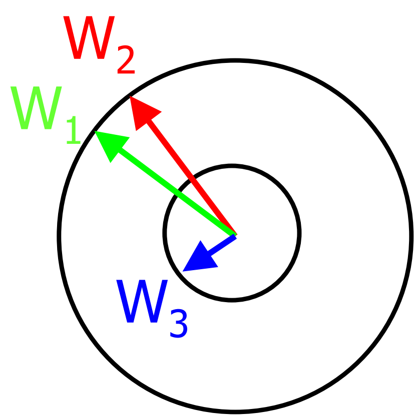




If $\delta << \lambda$: W_1 can be decomposed as sum of W_2 (direct, undiffracted light) and W_3 (light diffracted from object structures) where W_2 and W_3 are phase shifted by $\lambda/4$



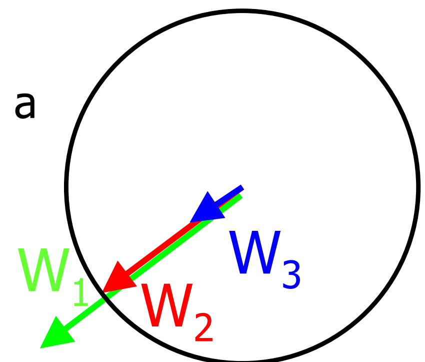
Amplitude sample:
Phase shift of $\lambda/2$ between direct & diffracted light:
W_1 significantly smaller than W_2 → good contrast



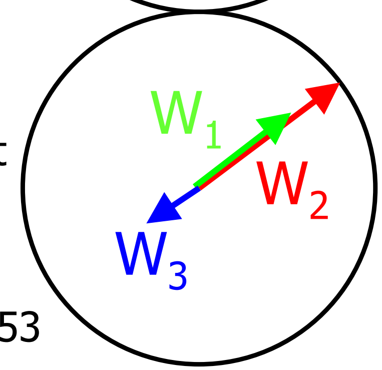
Phase sample:
W_1 has almost the amount as W_2 → weak contrast

How to increase the contrast?

Phase shifting of the undiffracted light W_2 using a phase ring



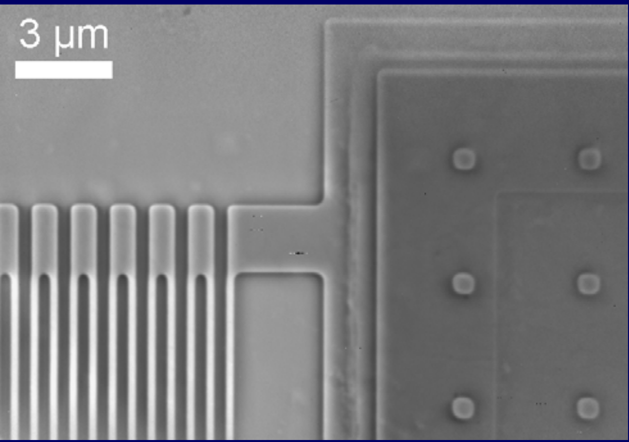
Phase shift $\lambda/4$:
Positive phase contrast
Object detail brighter

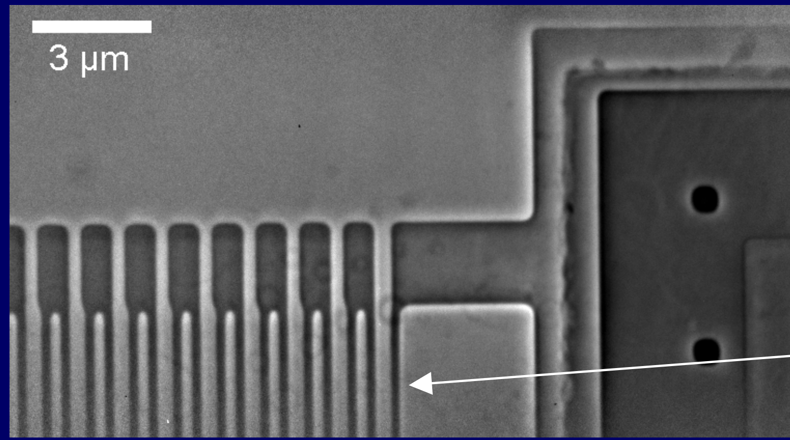


Phase shift $3\lambda/4$:
Negative phase contrast
Object detail darker

F. Zernike
nobel prize 1953

Phase contrast X-ray microscopy @ 4 keV – Applications I

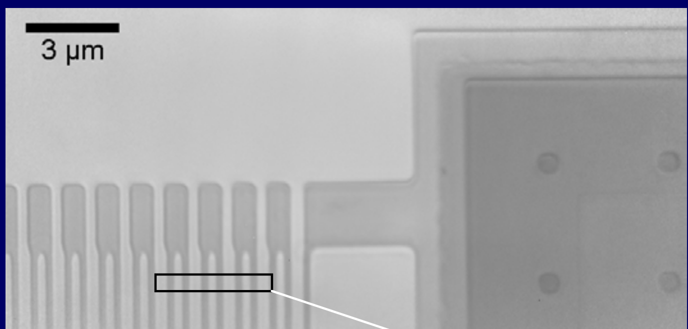




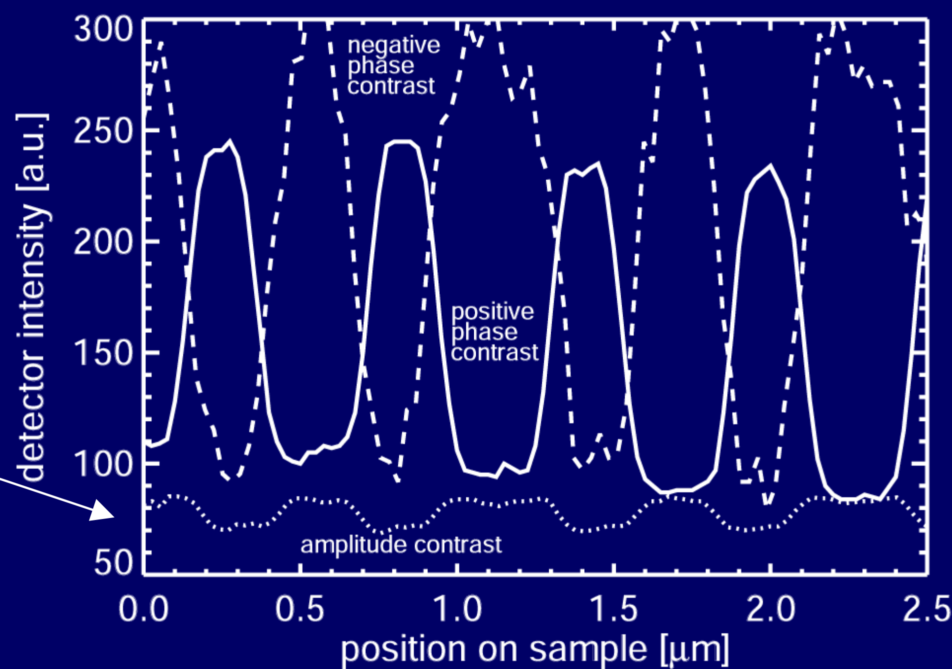
SEMATECH-Sample:
Copper Interconnects
within a SiO_2 dielectric
in a serpentine resistor,
smallest line width
225 nm

Positive phase contrast 45 %
(0.7 µm high Ni phase ring)

Negative phase contrast 40 %
(2.2 µm high Ni phase ring)



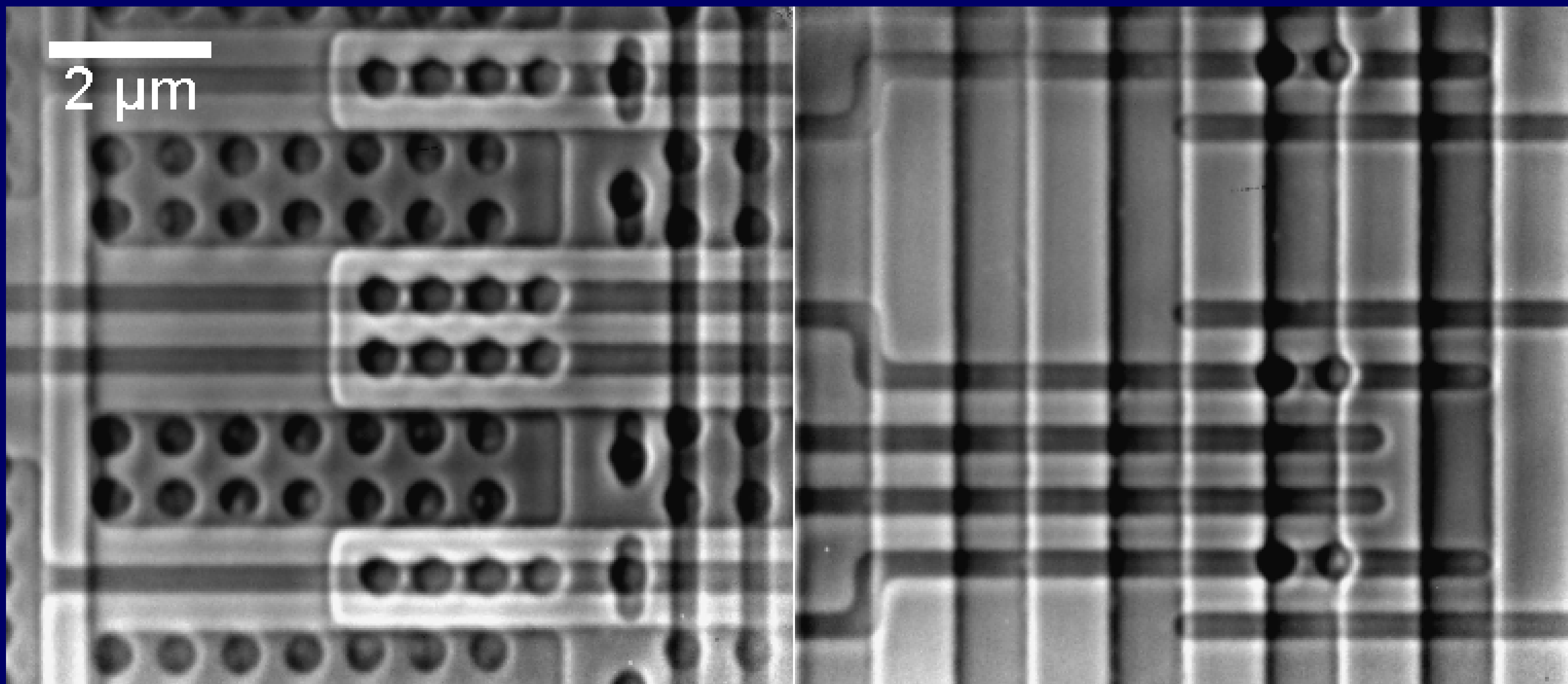
In comparison:
Amplitude contrast 7 %



Contrast reversal between:

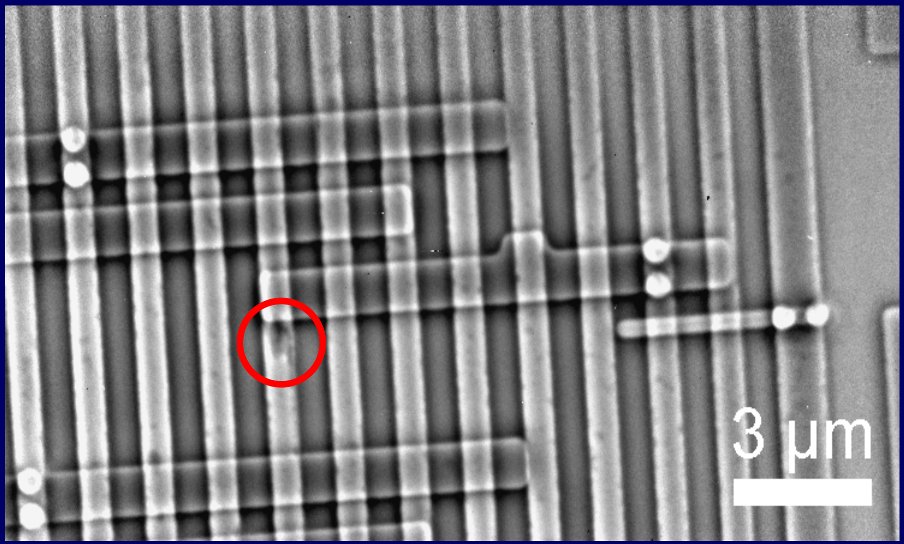
- Amplitude contrast and positive phase contrast
- positive and negative phase contrast image

Zernike Phase contrast @ 4 keV – Applications II



AMD next generation microprozessor:
Images in negative phase contrast

Zernike Phase contrast @ 4 keV – Applications III

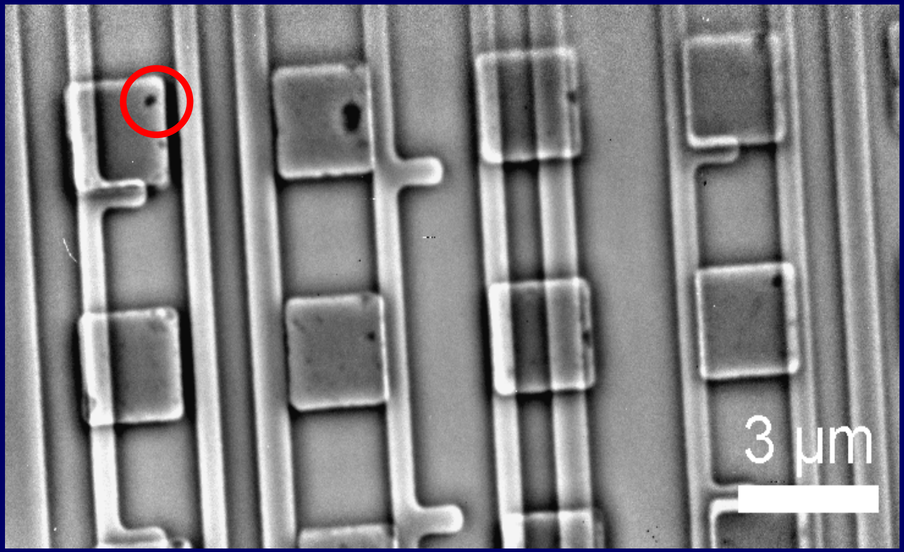


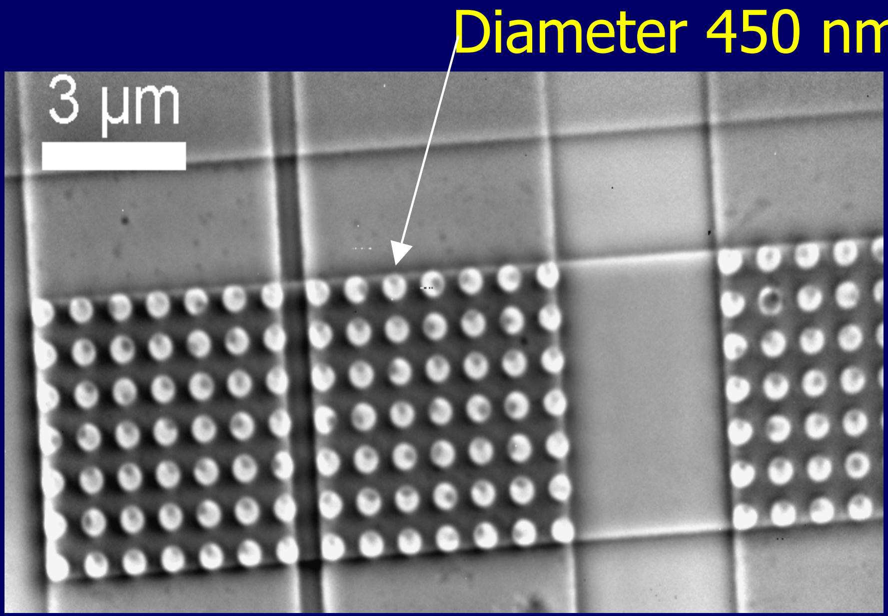
AMD-Sample:

Positive phase contrast images

Studies on defects in a microprocessor chip

Possibility of probing bulk material (20 µm thick)





Conclusions

Full-field X-ray microscope (TXM) using highly coherent undulator radiation:

High numerical aperture (N.A.) Fresnel zone plates with large diameter used as condenser

- provide incoherent or just partially coherent illumination required for full-field X-ray microscopy due to
  - high N.A. that allows use of a center stop to block the highly coherent on-axis 0^{th} order beam
  - a diameter larger than the lateral coherence length of the incident radiation at the experimental endstation
- provide matched N.A. illumination for employing high resolution zone plate objectives
- provide sufficient spatial separation of 0^{th} and 1^{st} diffraction orders so as to allow phase shift manipulation of the 0^{th} order (Zernike Phase contrast)

Summary and Outlook

Full-field X-ray microscope (TXM) in Zernike-type phase contrast mode

Zernike-type Phase contrast microscopy successfully demonstrated close to its theoretically predicted characteristics (resolution, contrast) in the several keV regime (4 keV)

Where to go next?

- Extend the applicability to different kinds of samples (biology, materials science etc.) by choosing matched phase rings
- High-resolution tomography:
    - Assumption of parallel projection for tomography is met
    - micro zone plate depth-of-focus & image field available: 3D imaging of a sample volume of 15 x 15 x 15 μm^3 at sub-100 nm resolution feasible